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HEATING EFFECTS AND ENDURANCE PROPERTIES OF THE 3" A.A. GUN M3 AS DETERMINED BY RAPID FIRE TESTS

by

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Project KC 65 - Tests to Determine the Rise of Temperature of Cannon Due to Firing and their Rate of Cooling.

Abstract

After 247 rounds of rapid fire, the gun and recoil mechanism was still functioning. The maximum observed temperature of the gun was 430 deg. C., which was about 110 deg. below the maximum allowable temperature. The maximum observed temperature of the recuperator oil was 95 C. Erosion was not excessive. Range dispersion did not increase appreciably during the firings. Comparison of the heating effects of pyro and NH powder were obtained, also, the effect of removing a portion of the band. Data were secured from which the heating effects, and the temperature at various rates of fire were computed.

Introduction

Rapid fire tests of the 3" A.A. Gun M3 were made with the object of testing the endurance properties of the gun and to test the gun to destruction if feasible. As a part of the test, star gauge measurements and range data were secured. This information is of value because it would not be advisable to fire at high temperatures if the erosion were excessive or if the accuracy decreased seriously. The determination of the heating effects was an important part of the test because this information leads to the establishment of permissible rates and duration of fire.

Firings Made

On March 29, 1935, 18 rounds were fired to establish the charges and on April 22, 1935, 55 preliminary rounds were fired. The preliminary rounds were fired mainly to determine the heating effects so that a computation could be made of the time at which the gun crew should take cover. As a part of this phase of the tests, data were secured on the heating effects of pyro and FNH powders and the effect of removing part of the rotating bands. On May 7, 1935, 247 rounds were fired as an endurance test. The attached firing record No. 8436 gives the description of the firings made.

The following table is included showing the projectile, charges, and velocities:

Date 1935	No. Rds.	3" Proof Projectile Weight lbs.	Lot	Powder Type	Powder Weight lbs.	Velocity f/s
Apr. 22	15	12.7	740	Pyro	4.84	2800
Apr. 22	15	12.7*	1337A	Pyro	4.12	2800
Apr. 22	25	12.7	3805	NH	5.00	2800
May 7	247	15.0	740	Pyro	4.81	2600

Measurement of Temperatures

The points of measurement of gun temperatures were on the outside of the barrel. Unless otherwise stated, the temperatures in this report refer to temperatures on the outside of the barrel.

Thermo-couples were used in obtaining the temperature. Two thermo-couples were welded to the gun, one at 1.08 ft. from the muzzle and one at 5.21 ft. from the muzzle. The 3" A.A. Gun M3 recoils in a sleeve and hence a welded thermo-couple could not be used at the breech. Therefore, a thermo-couple was attached to a brass plate which was held in place and pressed against the gun by a wooden frame built to conform to the shape of the gun. This thermo-couple was placed on the gun after the firings were over at a point 8.38 ft. from the muzzle. Figure 1 shows the position of the thermo-couples.

A thermo-couple was also placed in the oil by-pass between the recoil brake cylinder and the cylinder containing the floating piston of the recoil system. Entrance into the oil passageway was secured by removing the oil refilling plug

* Rotating band modified by cutting out the copper in the middle of the band leaving .02" flats at front and rear.

Note: The web thickness of Lots 740 and 1337 are .0443" and .0316", respectively.

and inserting a specially built plug containing the thermocouple.

Results of Preliminary Firings

The temperatures attained during the preliminary firings are shown in Plot 1. All of the preliminary rounds were made with the 12.7 lb. proof slug. The first 15 rounds were made with pyro powder and the standard or unmodified rotating band. The second 15 rounds were made with pyro powder and a rotating band modified by cutting out the copper in the middle of the band leaving only .02" flats at the front and rear of the band. The last group consisted of 25 rounds made with NH powder and the unmodified rotating band. The first and second conditions of firing gives the effect on the temperature rise of removing a portion of the rotating band, while the first and third conditions of firing gives a comparison of the heating effects of pyro and NH powders.

The following table shows the computed degrees rise per round, allowance being made for the cooling during firing:

Rotating Band	Type Powder	Temp. Rise Deg. C.	Distance from Muzzle ft.	Deg. C. Rise per round
Standard	Pyro	19-69	1.08	3.35
"	"	19-53	5.21	2.30
Modified*	"	51-93	1.08	2.80
"	"	43-73	5.21	2.00
Standard	NH	78-141	1.08	2.54
"	"	66-107	5.21	1.64

The general experience with the heating of guns has been that the temperature rise per round decreases as the temperature increases, which appears to be due to the increase in specific heat with the temperature and to the decrease in the difference between the temperature of the powder gases and the temperature of the gun. Since the heating effects were determined at different temperatures, it was desirable to make an adjustment for these factors. This was accomplished by calculating the heat absorbed which takes into consideration the increase in specific heat. Then, the values for the heat absorbed were adjusted to equal temperature ranges by the use of the more complete data of the endurance firings, a method which is described later in the report. The following table shows the results of the calculations:

* Modified by cutting out the copper in the middle of the band leaving .02" flats at the front and rear of the band.

Rotating Band	Type of Powder	Temp. Rise Deg. C	Dist. from Muzzle ft.	Heat Absorbed Cal. per rd. Per cm. length barrel	Heat Absorbed Cal. per rd. Per cm^2 bore surface	Computed Heat Absorbed if Initial Temp. were 19° C Per cm. length barrel	Computed Heat Absorbed if Initial Temp. were 19° C Per cm^2 bore surface
Stand.	Pyro	19-69	1.08	400	16.7	400	16.7
"	"	19-53	5.21	462	19.3	462	19.3
Mod.	"	51-93	1.08	336	14.1	344	14.4
"	"	43-73	5.21	402	16.8	409	17.1
Stand.	NH	78-141	1.08	308	12.9	330	13.8
"	"	66-107	5.21	331	13.9	347	14.6

From the above results it appears that the heat absorbed was appreciably less using the modified rotating band. Also, the heat absorbed was less when using NH powder as compared to the pyro powder.

Although the heat absorbed was appreciably lower when using the reduced rotating band, there are other important factors which need to be considered, namely, the density of the gases and their time of application, and the difference in temperature between the gases and the bore surface.*

In order to arrive at the temperature difference between the powder gas and bore surface, computations were made of the muzzle temperatures of the gases as follows: The initial temperatures of the gases of pyro and NH powders similar in composition to those used in the present investigation have been computed to be about 2700 and 2400 deg. C., respectively. From the weight and specific heat of the gases, one can compute the drop in temperature corresponding to the energy losses due to the velocity of the projectile, velocity of the gases, and heat absorbed by the gun. The following table shows the results of the computations.

Powder Type	Weight of Charge lbs.	3" Proof Proj. Weight lbs.	3" Proof Proj. Muzzle Vel. f/s	Temperature Powder Gases, Deg. C Initial	Temperature Powder Gases, Deg. C Muzzle
Pyro	4.84	12.7	2800	2700	1640
"	4.12	"	"	"	1500
NH	5.00	"	"	2400	1430

*'Report on the cooling of closed chambers' (in preparation) by R. H. Kent.

Considering the pyro powder, corresponding to the tests of the standard and modified rotating bands, the computed muzzle temperature of the gases is somewhat lower for the conditions of test of the modified band. Therefore, the effect of the temperature of the gases should be to reduce the heat absorbed under the conditions of tests of the modified band. Considering the pyro and NH powders, it appears that the initial and muzzle temperatures of the NH powder gas are appreciably lower than the pyro and, hence the heat absorbed by the gun should be appreciably less.

In making the calculation of the muzzle temperature of the gases, it was necessary to compute the total heat absorbed per round by the gun. These values are shown in the following table, including the energy of the powder and projectile:

Powder Type	Weight Charge lbs.	Total Energy* Charge, cal.	Total Heat Absorbed by Gun cal/rd.	Per Cent of Energy of Charge Absorbed by Gun	Energy of Projectile, cal.	Per Cent of Energy of Charge Imparted to Proj.
Pyro	4.84	1,720,000	183,000	11	502,000	29
"	4.12	1,470,000	163,000	11	502,000	31
NH	5.00	1,540,000	135,000	9	502,000	32

From the above results it appears that approximately 10 per cent of the energy of the powder is expended in heating the gun, and about 30 per cent in imparting velocity to the projectile.

Computation of bursting temperature of gun.

Since the rate of fire is much slower when the gun crew takes cover it was desirable to compute the temperature at which the gun crew should take cover in order to fire as many rounds as possible at the fast rate and thereby minimize the heat lost by cooling.

A computation was made by J. R. Lane of the maximum pressure occurring at various points along the bore. From the maximum allowable pressure curve for the gun and from the computed maximum pressures, the safety factors were obtained as a function of the distance along the bore. Report No. 812/2 "Tension Properties of Centrifugally cast molybdenum - vanadium gun steel at high and low temperature", Watertown Arsenal, furnishes data regarding the reduction in strength of gun steel with increase in temperature. Making use of

* The energies of the pyro and NH powders were taken as 1,100,000 and 950,000 ft.lbs. per lb. which appears to be representative for the powders used.

these data, the temperature was found at which the safety factor was reduced to unity, or in other words, the temperature at which failure should occur. The results are shown in Plot 2 which shows the maximum allowable temperature as a function of the distance along the bore. Then, from the heating effect per round, the number of rounds necessary to reach the bursting temperature was calculated, taking into account the cooling. After making allowances for safety it was decided to take cover when the temperature at the thermocouple 5.21 ft. from the muzzle reached 250° C.

Results of endurance tests.

Cover was taken after 125 rounds of rapid fire at an average rate of 17.4 rounds per minute. After firing 4 rounds from cover, a delay of about 5 minutes occurred due to trouble in removing a round which would not go into the chamber. A burst of 20 rounds was then fired rapidly, after which cover was taken for the remaining rounds. The rate of fire from cover averaged 7.1 rounds per minute. Firing was stopped after 247 rounds because the supply of ammunition at the gun was exhausted.

Some trouble was experienced with the operating cam at the beginning of firing making it necessary to operate the breech block by hand for a few rounds. The cartridge case of one round would not go into the chamber because of a burr on the rim of the base, causing a delay while removing the slug and powder charge. The recoil mechanism functioned smoothly throughout the test.

Erosion of Gun

Plot 3 shows the erosion of the lands and grooves as a result of the rapid fire tests. Before the rapid fire tests, there was no evident erosion of the lands or grooves except for the usual rather marked erosion near the origin of rifling. There was some deposit of copper in the rear half of the rifling and practically none in the forward half. After the rapid fire tests were completed the rifling was apparently in good condition. There was some further erosion of the lands and grooves near the origin of rifling and practically no change in the diameter over the remaining portion of the barrel. Photographs No's. 33345 and 33345A show gutta percha impressions at the muzzle and origin of rifling.

Although the erosion apparently was not excessive, it appears that the firing of 247 rounds rapid fire at high temperatures should cause a greater reduction in the accuracy life of the gun than would a corresponding number of rounds fired at near atmospheric temperature. Erosion tests of caliber .30 tank type machine guns showed that the accuracy life was considerably reduced by firing at high temperatures.

Comparing the erosion of the 105 mm A.A. Gun M1* with that of the 3" A.A. Gun M3 in the present investigation, it appears that 169 rounds of rapid fire in the 105 mm Gun produced a very rapid erosion whereas the 247 rounds of rapid fire in the 3" Gun produced only a moderate erosion.

Range Observations

Range observations were made for the purpose of determining whether there was any change in the range accuracy during the rapid fire. The accuracy of the gun as affected by the temperature is of considerable importance, since if there is a serious decrease in the accuracy of the gun at high temperatures it would not be desirable to use the gun at such temperatures, even though it were possible to do so without damage to the gun.

Observations were made of the range of about every third round during approximately the first half of the fire when the gun crew was not taking cover and of about two rounds out of three while taking cover.

For the purpose of computing the probable errors, the firings were divided into four groups of 62, 62, 62, and 61 rounds each. Because of the difference in the rate of fire, there were about one-half as many observations in the first and second groups as in the third and fourth groups. In order to eliminate the effect of a shift in range during firing, the probable errors were computed by the method of successive differences. In this connection, precautions were taken that the elevation of the gun did not change during the firings. The following table shows the computed probable errors:

Rounds	Gun Elev. deg.	No. Rds.	No. Obser-vations	Mean Range yds.	Range P.E. of one rd. yds.	P.E. of P.E. yds.	Remarks
1-62	29	62	21	6657	128	14	Rapid fire
63-124	29	62	21	6716	86	9	" "
125-186	29	62	39	6608	69	5	From cover
187-247	29	61	40	6597	108	8	" "

* Heating Effects and Endurance Properties of the 105 mm A.A. Gun M1 as Determined by Rapid Fire Tests, Feb. 12, 1936.

From the above results, the range P.E. decreased during the firings and then increased for the last group, However, in view of the rather large P.E. of the P.E. it is believed that the decrease in range error is not significant.

It is plausible that the range error might increase due to erosion and to the expansion of the bore as a result of the increase in temperature. As regards erosion, star gauging measurements show that the erosion apparently was not great enough to cause an appreciable change in the accuracy. As regards expansion of the bore, computations show that for an increase in temperature of 350 deg. C, the diameter of the bore should increase about .011 inch which could plausibly diminish the accuracy.

Heating Effects of Endurance Firings

Plot 4 shows the temperatures of the gun and recuperator during the endurance firings and for the cooling period after the firing. The thermocouples at 1.08 and 5.21 ft. which were welded to the gun functioned very satisfactorily. The recuperator thermo-couple also functioned well. The thermocouple which was placed on the breech after the firing was over apparently did not give a normal temperature curve since the observed temperature increased practically 100 per cent over a period of about 30 minutes after the firing stopped. It is likely that the wood frame holding the thermocouple may have been warped by the high temperatures of the gun, thus causing varying degrees of contact between thermocouple and gun. Because of the uncertainty regarding the breech temperature, the data from this thermo-couple were not used in any of the calculations.

As will be noted from Plot 4, the firings were divided into two groups. In the first group nearly all rounds were fired without taking cover whereas nearly all the rounds of the second group were fired from cover. Making allowance for the cooling, the degrees rise per round was computed for each group, and also for the two groups considered as one. The following table shows the results of the computations:

Temp. Range Deg. C	Distance from Muzzle ft.	Deg. C. Rise per rd.
20-336	1.08	2.64
314-450	"	1.98
20-450	"	2.18
20-253	5.21	1.87
244-369	"	1.40
20-369	"	1.59

The greatest degrees rise per round was obtained at the muzzle. The degrees rise per round decreased with increase in temperature.

The heat absorbed per round, which takes into consideration the increase in specific heat with increase in temperature, was calculated with the following results:

Temp. Range	Distance from Muzzle ft.	Heat Absorbed Calories per round per cm. length barrel	Heat Absorbed Calories per round per $cm.^2$ bore surface
20-336	1.08	334	14.0
314-450	"	291	12.1
20-450	"	288	12.0
20-253	5.21	388	16.2
244-369	"	320	13.4
20-369	"	341	14.2

The heat absorbed per round was slightly greater at 5.21 ft. than at 1.08 ft. from the muzzle, whereas in the case of the degrees rise per round the reverse was found because of the smaller heat capacity at the muzzle.

Computed heating effects with 12.7 lb. projectile

The endurance tests were made with the 15. lb. proof projectile and because of the large number of rounds fired the heating effects were determined over a rather large temperature range. The heating effects using the 12.7 lb. proof projectile were determined by firing 20 rounds in the preliminary firings which resulted in a rather small temperature range. It was desirable to extend the values of the heating effects with the 12.7 lb. projectile which is the weight of the service projectile to higher temperature range. With this extension the temperatures attained at various rates of fire could be computed under service conditions. The method of computation, which was suggested by R. H. Kent, is as follows:

Use is made of the equation

$$H = a - b\theta$$

where H is the heat absorbed per round for the temperature rise θ, and a and b are constants. Values of a and b were computed to be 462 and .403, respectively at 1.08 ft. from the muzzle; 482 and .405 at 5.21 ft. from the muzzle.

Having determined a and b, the heat absorbed was calculated over the temperature range corresponding to the tests of the 12.7 lb. projectile. The heat absorbed using the 12.7 lb. projectile was then calculated for the temperature ranges corresponding to the tests of the 15 lb. projectile by simple proportion. The degrees rise per round was computed by dividing the heat absorbed by the heat capacity. The following table shows the results of the computations for the 12.7 lb. projectile.

Temp. Range Deg. C.	Distance from Muzzle ft.	Heat Absorbed cal. per rd. per cm. length barrel	Heat Absorbed cal. per rd. per $cm.^2$ bore surface	Deg. C. Rise per rd.
19-69	1.08	400	16.7	3.35
20-336	"	302	12.7	2.39
314-450	"	263	11.0	1.79
20-450	"	261	10.9	1.97
19-53	5.21	462	19.3	2.30
20-253	"	383	16.0	1.85
244-369	"	316	13.2	1.38
20-369	"	337	14.0	1.57

After making this adjustment the heating effects computed for the 12.7 lb. projectile are almost exactly the same as for the 15 lb. projectile at 5.21 ft. from the muzzle. At 1.08 ft. from the muzzle, the calculated heating effects are slightly greater for the 15 lb. projectile.

A computation was made of the muzzle temperatures of the gases under the conditions of test of the 12.7 and 15 lb. projectiles with the following results:

Powder Type	Powder Wt. of Charge lbs.	Projectile Wt. lbs.	Projectile Muzzle Vel. f/s	Temperature of Gases Initial Deg. C.	Temperature of Gases Muzzle Deg. C
Pyro	4.81	12.7	2800	2700	1640
"	4.84	15	2600	"	"

From the above results, it appears that the effect of the temperature of the gases on the heat absorbed should be about the same for the two conditions of test.

Aside from the weight, the projectiles differ in respect to the band width, the 12.7 lb. projectile having nearly twice the band width.

It is of interest to consider the value of the constants a and b in respect to the theoretical temperature at which no heat would be absorbed by the gun. From the values of a and b determined by the observed temperature rise at the muzzle, the calculated temperature at which no heat is absorbed is about 1150 deg. C. The computed muzzle temperature of the gases is 1640 deg. C and at this temperature of the gun no heat should be absorbed. Considered in another manner, the value of b computed from the observed temperature rise is about .40, while the value of b obtained from the computed muzzle temperature of the gases is about .28.

Temperature rise at various rates of fire.

The temperature rise at various rates of fire was computed for the gun making allowance for the cooling and using the heating effects for the 12.7 lb. projectile. The results are shown in Plot 5.

From this plot it is seen that at a rate of fire of 5 rd/min. the cooling is a very important factor in the temperature rise of the gun. At rates of fire of 10 rds/min. and above, the cooling is relatively unimportant for the temperature range considered.

The maximum allowable temperature at 1.08 ft. from the muzzle is 545° C and at 5.21 ft. it is 470° C as shown in Plot 2. At 5 and 10 rds/min. the maximum allowable temperature will be reached first at the point 5.21 ft. from the muzzle, but at 15 and 20 rds/min., the maximum allowable temperature will be attained at both points of measurement at practically the same time. Hence in computing the rounds necessary to heat and maintaim the gun at various temperatures the results from the thermocouple 5.21 ft. from the muzzle were used. The results of the computation follow:

Temperature at 5.21 ft. from Muzzle Deg. C above Atmospheric	Number Rounds Necessary to Heat at 5 rds/min	at 10 rds/min	at 15 rds/min	at 20 rds/min	Rounds per min. Necessary to Maintain Temperature
100	66	64	64	63	.5
200	140	133	130	129	1.1
300	230	206	200	197	1.8
400	343	287	274	268	2.6
470*	448	348	327	318	-

* The gun should burst at this excess temperature according to the computations, if the initial temperature is assumed at 0° C.

From the table on page 11, one would fire, for example, 66 rounds at 5 rds/min. to heat the gun 100° C above atmospheric and then .5 rds/min. would maintain this temperature. Also, it should require 448 rounds at 5 rds/min. or 318 rounds at 20 rds/min. to attain the calculated bursting temperature of 470° C at 5.21 ft. from the muzzle. Although rates and duration of fire are computed up to the bursting temperature of the gun, practical temperatures of firing would be considerably lower because of safety reasons and possible excessive wear or damage to the gun and its operating parts.

Computation of Cooling Constants and Emissivity.

The cooling constants were computed by the equation

$$k = \frac{\theta_2^{-.23} - \theta_1^{-.23}}{.23(t_2 - t_1)}$$

where θ is the excess temperature above atmospheric and t the time.

The emissivity was computed from the equation*

$$E = \frac{\rho c k(r_o^2 - r_i^2)}{2r_o}$$

where ρ is the density, c the specific heat, k the cooling constant, and r_o and r_i the outer and inner radii.

The following table shows the results of the computations:

Date of Test	Wind Direction and M.P.H.	Distance from Muzzle ft.	Cooling Coefficient k $\deg^{-.23}\min^{-1}$	Emissivity E Cal.cm^{-2} $\deg^{-1.23}\min^{-1}$
Apr. 22	N 7	1.08	.0037	.0097
"	" "	5.21	.0026	.0093
May 7	W 10	1.08	.0047	.0124
"	" "	5.21	.0026	.0093

* Third Partial Report in Connection with the test of the 3" A.A. Gun T8 and Mount T-3, O.P. 5228, Oct. 1934.

A higher k was obtained at the muzzle on May 7 than on April 22, but at the point 5.21 ft. from the muzzle the k's were the same for both dates of test. In view of the somewhat higher wind velocity of May 7, it might be expected that greater k's would be obtained on that date. The emissivities for the tests of April 22 were approximately equal for both points of measurements, but on May 7 a higher emissivity was obtained at the muzzle.

Computation of bore temperature.

The temperature at the bore surface was computed in general accordance with the method outlined in an earlier report*. The method, which was developed by R. H. Kent, was discussed in detail in the earlier report and will be only briefly referred to in the present report. The assumption is made that after a certain time interval the rate of temperature rise is a constant, that is, that it is independent of the distance from the axis of the bore and of the time. The general equation for the temperature is as follows:

$$u = At + B \log r + Cr^2 + D.$$

In the above equation, u is the temperatures, t the time, r the distance from the axis of the bore, and A, B, C, and D are constants.

The results of the computations of the bore temperature including the observed temperature at the outside surface are shown in the following table:

Rounds fire	Rate of fire rds/min.	Distance from muzzle ft.	Observed Temp. at end of firing Deg. C	Computed Temp. at bore surface Deg. C	Diff. in Temp. Deg. C
0-129	18.2	1.08	290	367	77
130-247	7.8	"	420	456	36
0-129	18.2	5.21	220	342	122
130-247	7.8	"	347	398	51

The highest observed temperatures and also the highest computed bore temperatures occurred at the point of measurement nearest the muzzle. However, the greatest computed difference in temperature between inside and outside occurred at the point 5.21 ft. from the muzzle.

* Heating Effects and Endurance Properties of the 105 mm A.A. Gun M1 as determined by rapid fire tests, Feb. 12, 1936.

No allowance was made for the clearance between tube and liner which in effect would increase the temperature difference between inside and outside of the barrel. Because of the uncertainty as to what the actual clearance was at a given point in the gun, it was not thought advisable to make this calculation. However, in the case of the 105 mm A.A. Gun M1 which had the same nominal clearance, it was computed that for conditions of maximum clearance and assuming the clearance was filled with grease, that the temperature drop across the gap during firing should be about 30° C.

Recuperator temperature

The recuperator temperatures obtained in the preliminary firings are shown in plot 1 and those of the endurance firings are shown in plot 4. The latter temperatures are also shown in larger scale on plot 6.

From an examination of these plots it appears that the oil temperature drops rapidly after the firings are over and soon assumes a constant value which is somewhat higher than the initial temperature. Apparently the oil loses heat to the recuperator parts until the two reach the same temperature and then the temperature remains almost constant.

In computing the heating effect and cooling constant of the oil, it would obviously be in error to disregard the rise in temperature of the recuperator. Hence, it was necessary to develop some method of making allowance for this temperature rise and for this purpose, the method described in the attached appendix was used.

By application of the method to the data shown in Plot 6, values of the cooling constants and the deg. C rise of the oil were calculated as follows:

Firings	Cooling Constant of oil "k_1"	of recuperator "k_2"	Deg. C. rise per round of oil, "h"
1st group	.26	.023	1.07
2nd group	.20	.023	1.38

With reference to the above cooling constants, it is likely that the oil in the vicinity of the thermo-couple may cool faster than the main body of the oil. The reason for this inference is that there is a much greater ratio of metal to oil in the constricted oil by-pass than in the brake cylinder where the diameter is much larger.

However, during the firings, the oil should be mixed by the movement of the piston and hence an average temperature of the oil should be obtained while the firing is going on.

The heat capacity of the oil and recuperator should be inversely proportional to the cooling constants and from this relation, the heat capacity of the recuperator is computed to be 10 times that of the oil. Since the recuperator contains 10.7 lbs. of oil, the oil will require about 2280 cal. per deg. C rise, and consequently the recuperator will require about 22,800 cal. per deg. C rise. The weight of the recuperator calculated from the heat capacity is 434 lbs. which agrees well enough with the actual 425 lbs. However, when one considers that much of the recuperator mechanism, is not in contact with the oil, it appears that the calculated weight should have been somewhat less.

Since the temperature rise of the oil and recuperator combined was 34 deg. C and since there were 247 rounds fired, the heat absorbed by the oil and recuperator is calculated to be 3450 cal. per round.

From the principle of the conservation of momentum, the recoil velocity of the gun is computed to be 25.5 f/s. With this recoil velocity of the gun, the recuperator must absorb about 23,300 ft. lbs. of energy per round which is equivalent to 7540 cal. per round. Since it was calculated from the temperature data that 3450 cal. per round were absorbed by the oil and recuperator, it appears that about one-half of the recoil energy is accounted for in this manner.

There are several factors which may account for the remaining energy. It is apparent that not all of the recoil energy is absorbed by the oil. A part of it is expended in friction in the recoil sleeve and in the various packing and pistons. Also, during the compression of the gas its temperature is raised, which would tend to heat the cylinder walls. Then, the cooling of the recoil system may have been a greater factor than was evident from the data. As regards this last factor, there was no observed cooling since a constant temperature was attained, and consequently no allowance could be made for the cooling of the recoil system.

<u>Summary</u>

1. As a result of the preliminary firings, it was observed that less heat was absorbed when a portion of the rotating band was cut away. However, other factors, particularly the difference in temperature between the powder

gases and the bore surface, may have been of greater effect than the band width. The use of NH powder resulted in a lower heat absorbed than the use of pyro powder, which appears to be due to the lower temperature of the gases.

2. A total of 247 rounds was fired as an endurance test without causing failure of the gun. The maximum observed temperatures attained were 430 and 360 deg. C at 1.08 and 5.21 ft. from the muzzle. These temperatures were about 110 deg. C lower than the computed maximum allowable temperature at which failure should occur.

3. The gun and recoil mechanism functioned well during the test. The only delay in the firings occurred while removing a round which would not go into the chamber.

4. Star gauge records made before and after the firings show that there was practically no increase in the diameter of the lands or grooves, except for the usual rather marked erosion near the origin of rifling.

5. The range dispersion did not increase appreciably during the endurance firings.

6. The degrees rise per round with the use of the 12.7 lb. service projectile and the temperature range covered by the endurance firings were 1.97 and 1.57 at 1.08 and 5.21 ft. from the muzzle, respectively. Corresponding values for the heat absorbed were 261 and 337 cal. per rd. per cm. length of barrel.

7. The greatest computed temperature difference between the outside of the barrel and the bore surface occurred at 5.21 ft. from the muzzle where a difference of 122 deg. C was obtained.

8. The maximum observed temperature of the oil in the recuperator was 95 deg. C. The degrees rise per round of the oil was calculated to be 1.07 and 1.38 for the first and second groups of firings.

9. According to the calculations, the maximum number of rounds that can be fired at various rates of fire before attaining the maximum allowable temperature are as follows: 448 rounds at 5 rds/min., 348 rounds at 10 rds/min., 327 rounds at 15 rds/min., or 318 rounds at 20 rds/min.

N. A. Tolch

N. A. Tolch.

H. H. Zornig.

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Lt. Col., Ord. Dept.,
Chief Research Division

NAT/emh
Aberdeen Proving Ground, Md.
March 4, 1936

APPENDIX
METHOD OF COMPUTING HEATING EFFECTS OF RECUPERATOR

In computing the heating effect and cooling constant of the oil, it would obviously be in error to disregard the rise in temperature of the recuperator. Hence, it was necessary to develop some method of making allowance for this temperature rise and for this purpose, the following method was suggested by R. H. Kent:

The assumption is made that the cooling of the oil and the heating of the recuperator are proportional to the difference in temperature between the oil and recuperator. Making this assumption, the following equations are obtained:

For the cooling of the oil,

$$\frac{d\theta_1}{dt} = -k_1(\theta_1 - \theta_2),$$

for the heating of the oil during firing,

$$\frac{d\theta_1}{dt} = nh - k_1(\theta_1 - \theta_2),$$

for the heating of the recuperator mechanism,

$$\frac{d\theta_2}{dt} = +k_2(\theta_1 - \theta_2),$$

where

θ_1 = temperature of the oil

θ_2 = temperature of the recuperator

k_1 = Cooling constant of the oil

k_2 = Cooling constant of the recuperator

n = Rate of fire

h = Degrees rise of oil per round.

The above equations were applied to the temperature data for the recuperator. A plausible curve for θ_2 was drawn in as a first approximation. Then, a first approximation of k_2 was obtained from the equation

$$k_2 = \frac{\theta_2}{\int_0^t (\theta_1 - \theta_2)\, dt}$$

In the above equation, the value or θ_2 is assumed to be equal to the observed θ_1 when θ_1 becomes constant. Having determined an approximation of k_2, θ_2 was computed as a function of the time from the equation

$$\theta_2 = k_2 \int_0^t (\theta_1 - \theta_2)\, dt$$

The calculations of k_2 and θ_2 were repeated until there was no further appreciable change in the successive approximations.

The cooling constant k_1 and the degrees rise per round h for the oil were next computed. k_1 is obtained from the equation

$$\frac{d\theta_1}{dt} = k_1(\theta_1 - \theta_2)$$

or

$$\log_e(\theta_1 - \theta_2) = k_1 t + \text{constant.}$$

The slope of $\log(\theta_1 - \theta_2)$ plotted against t determines the value of k_1. Since there was a stoppage in the firings resulting in two cooling curves, two values of k_1 were determined.

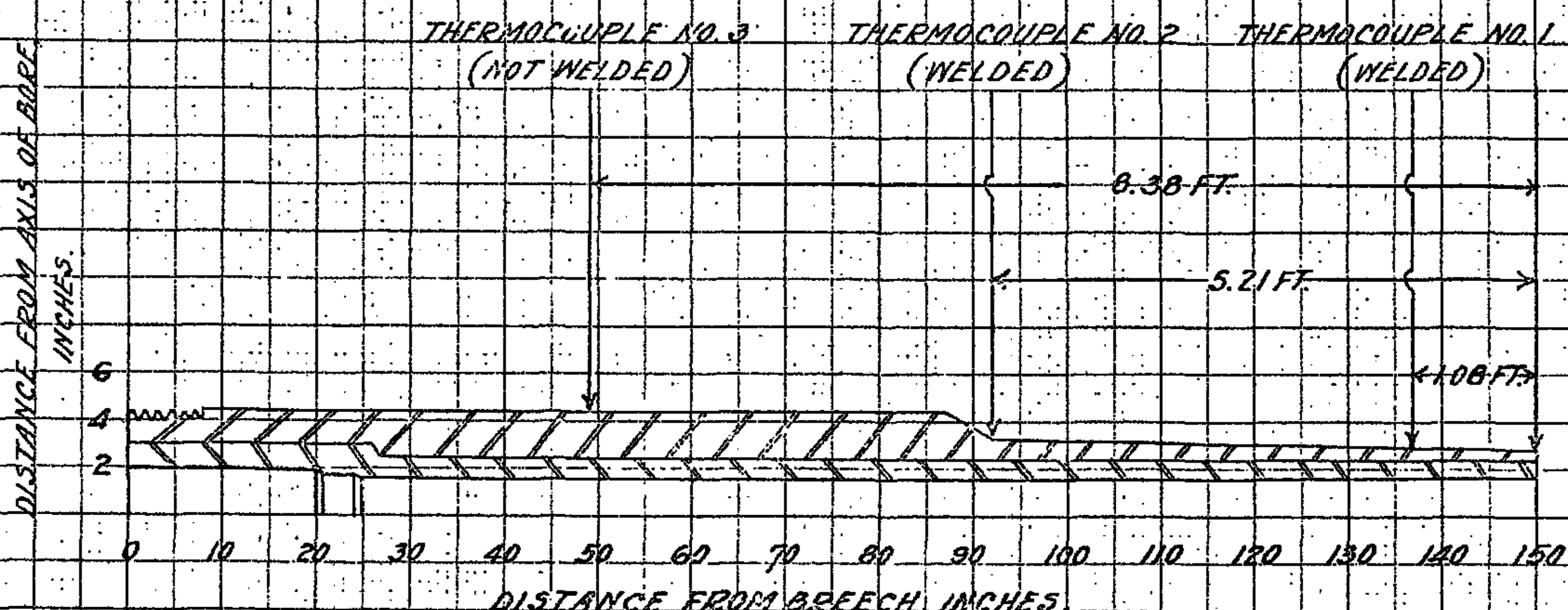
The degrees rise per round was determined by the equation

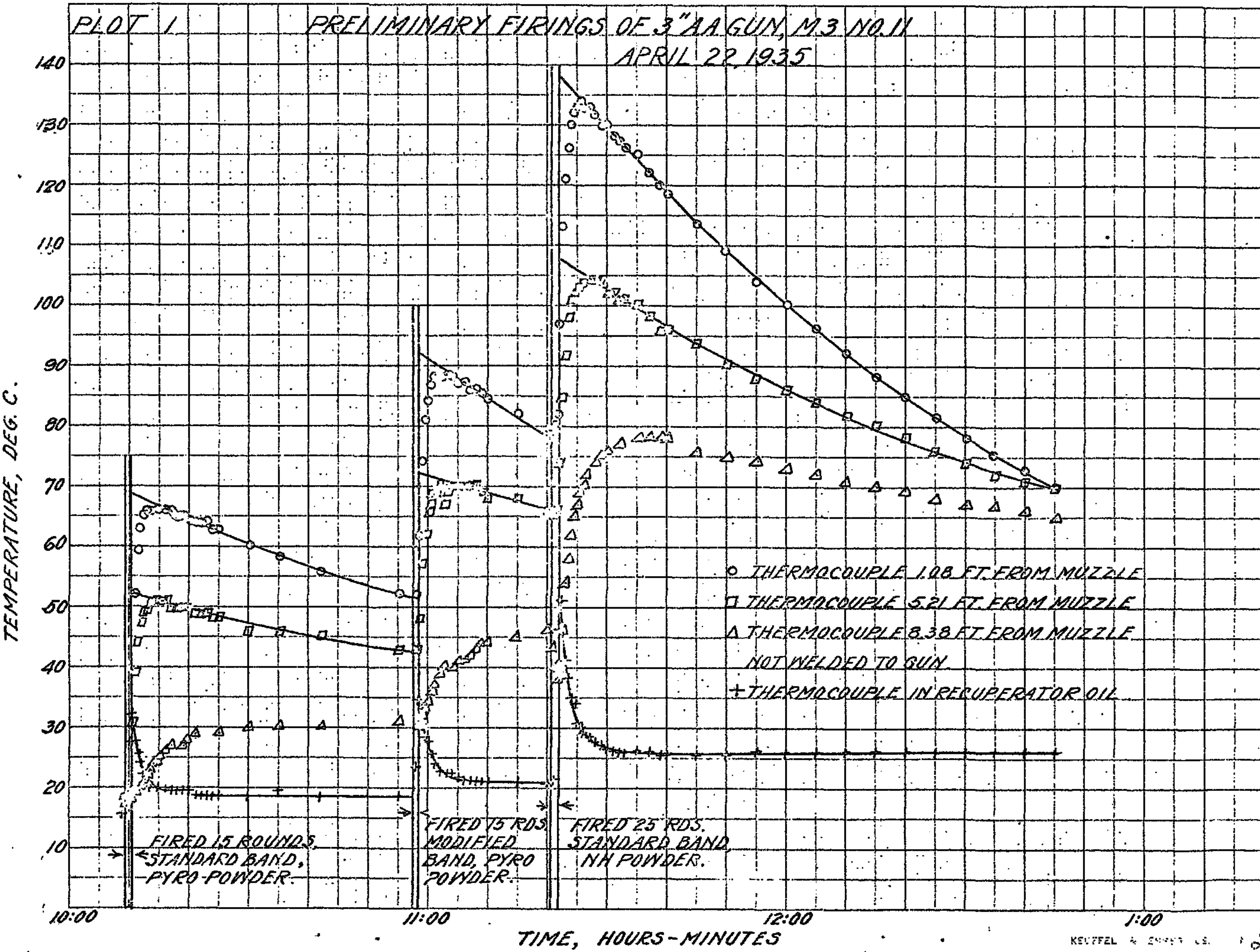
$$\theta_1 = \int_0^t \left[nh - k_1(\theta_1 - \theta_2)\right] dt$$

A value of h was assumed and a computation made to determine whether the computed θ_1 was equal to the observed θ_1 at the end of firing. If not, other values of h were selected until a value was found with which the computed θ_1 was equal to the observed θ_1. The degrees rise per round was computed for both groups of firings which were separated by the short stoppage in firing.

FIGURE 1.

SKETCH OF 3" A.A. GUN, M3.
SHOWING POSITION OF THERMOCOUPLES




PLOT 1
PRELIMINARY FIRINGS OF 3" AA GUN, M3 NO. 11
APRIL 22, 1935
TEMPERATURE, DEG. C.
140
130
120
110
100
90
80
70
60
50
40
30
20
10
10:00
11:00
12:00
1:00
TIME, HOURS-MINUTES
○ THERMOCOUPLE 1.08 FT. FROM MUZZLE
□ THERMOCOUPLE 5.21 FT. FROM MUZZLE
△ THERMOCOUPLE 8.38 FT. FROM MUZZLE NOT WELDED TO GUN.
+ THERMOCOUPLE IN RECUPERATOR OIL
FIRED 15 ROUNDS, STANDARD BAND, PYRO-POWDER.
FIRED 15 RDS. MODIFIED BAND, PYRO POWDER.
FIRED 25 RDS. STANDARD BAND, NH POWDER.
KEUFFEL & ESSER CO.

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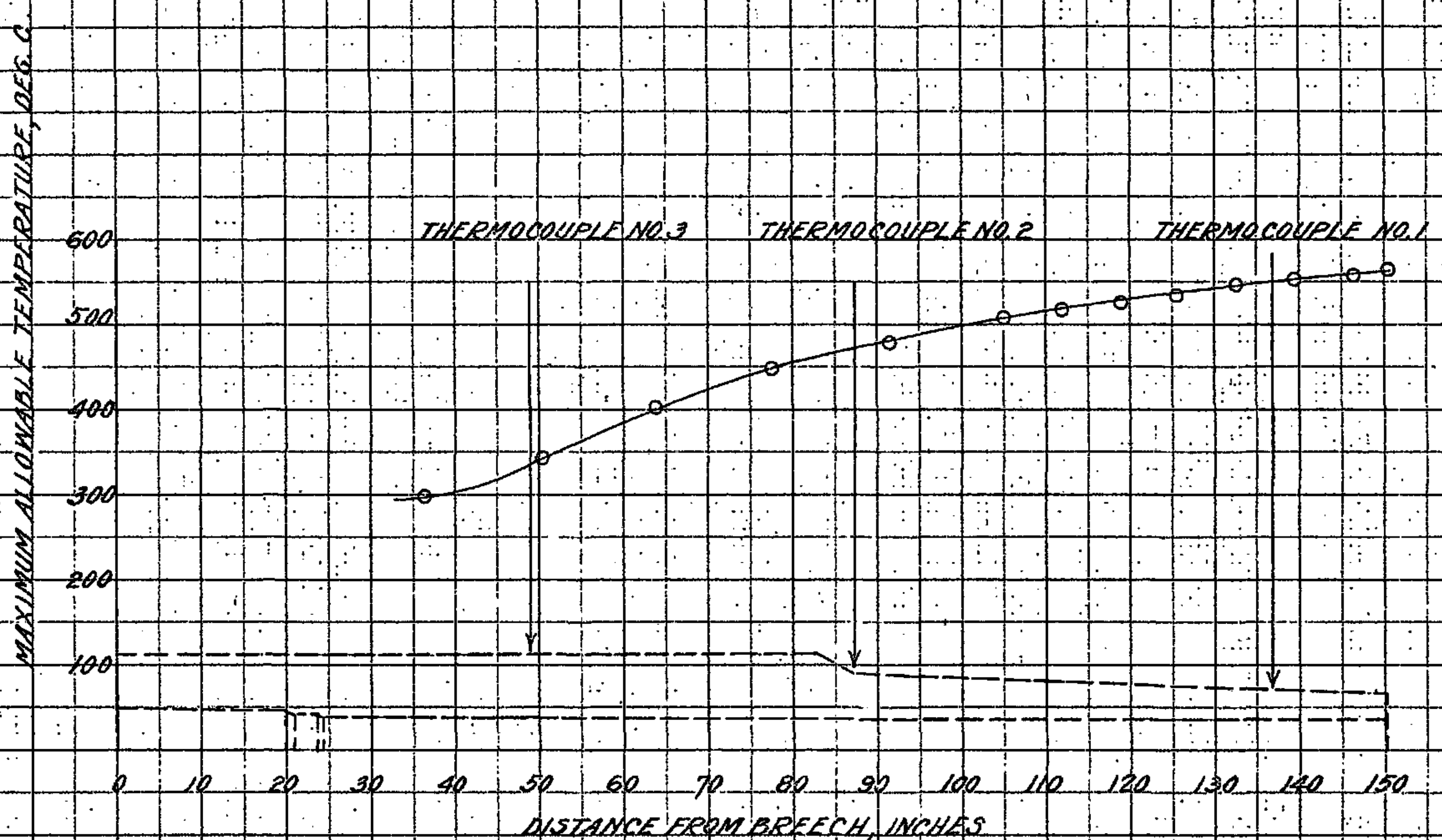
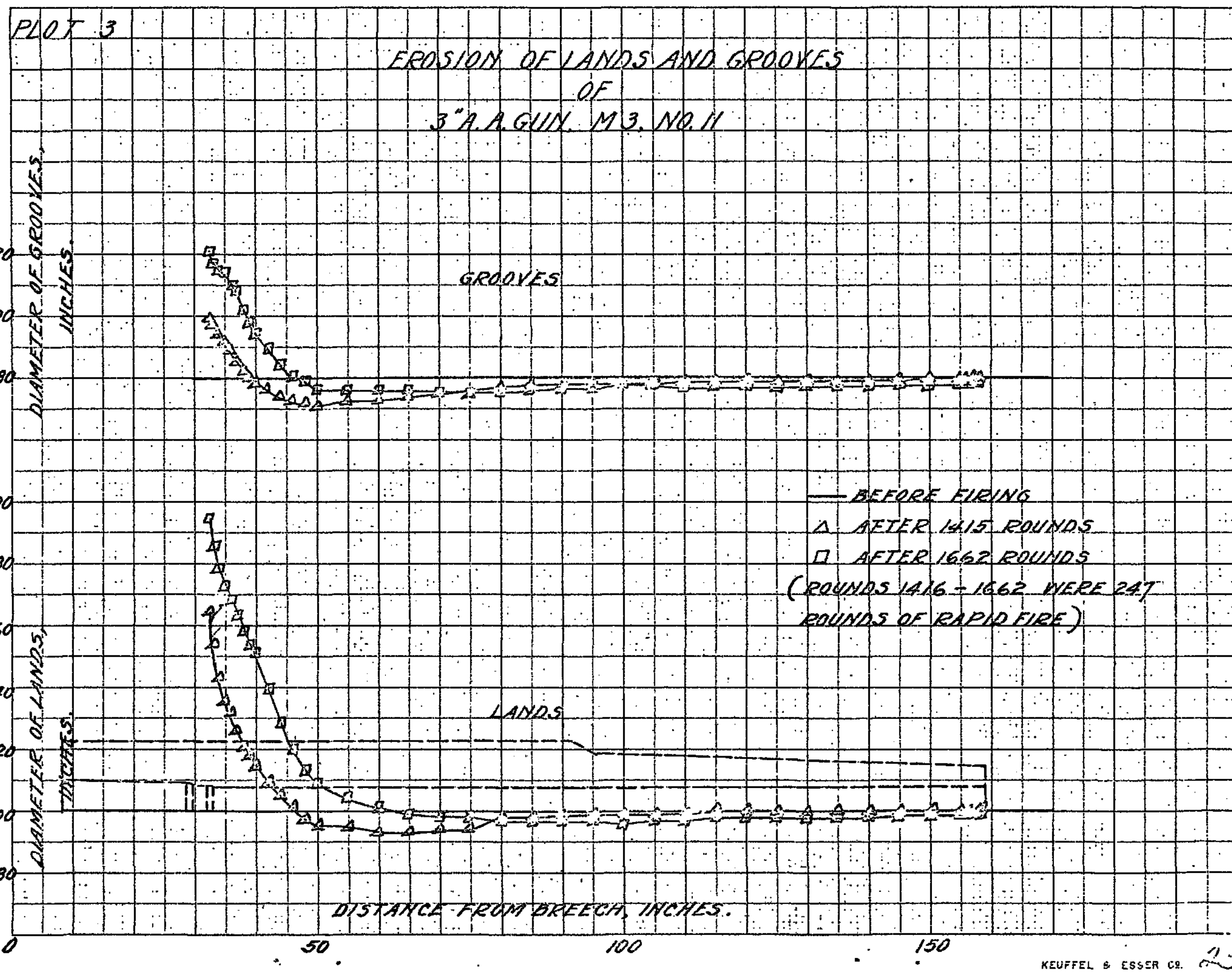
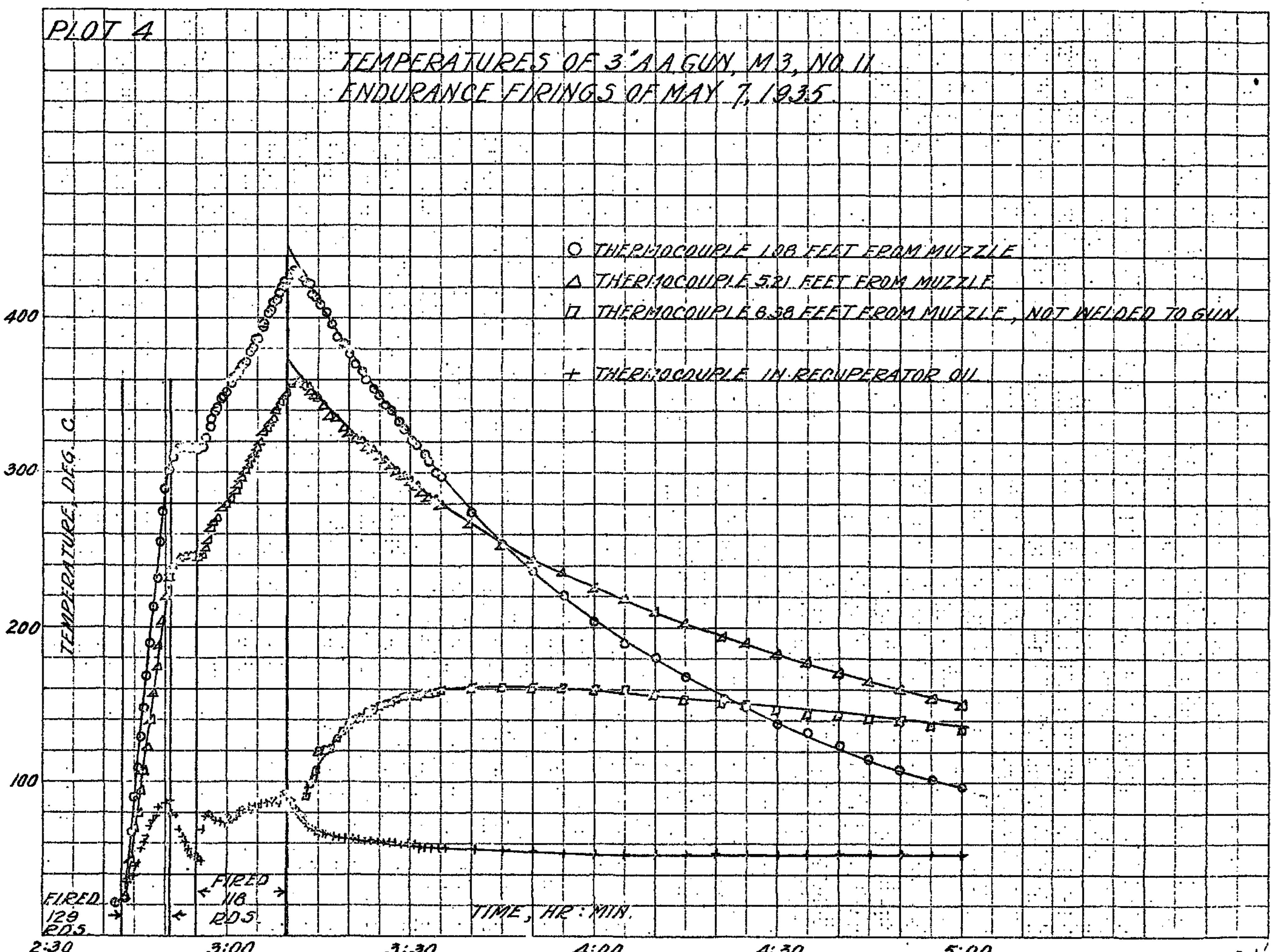
PLOT 2

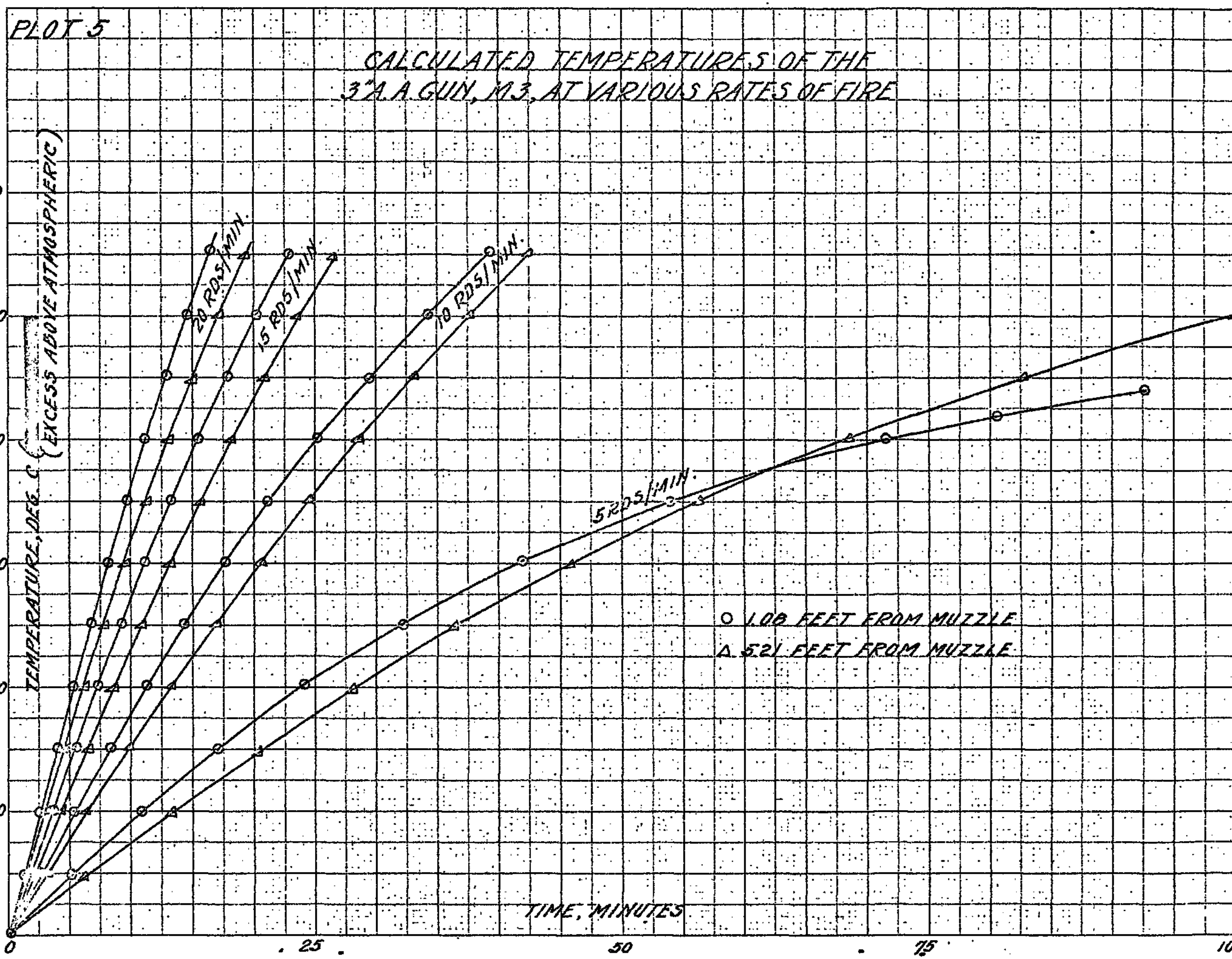
MAXIMUM ALLOWABLE TEMPERATURE
VS
DISTANCE FROM BREECH.
3" A.A GUN M3.

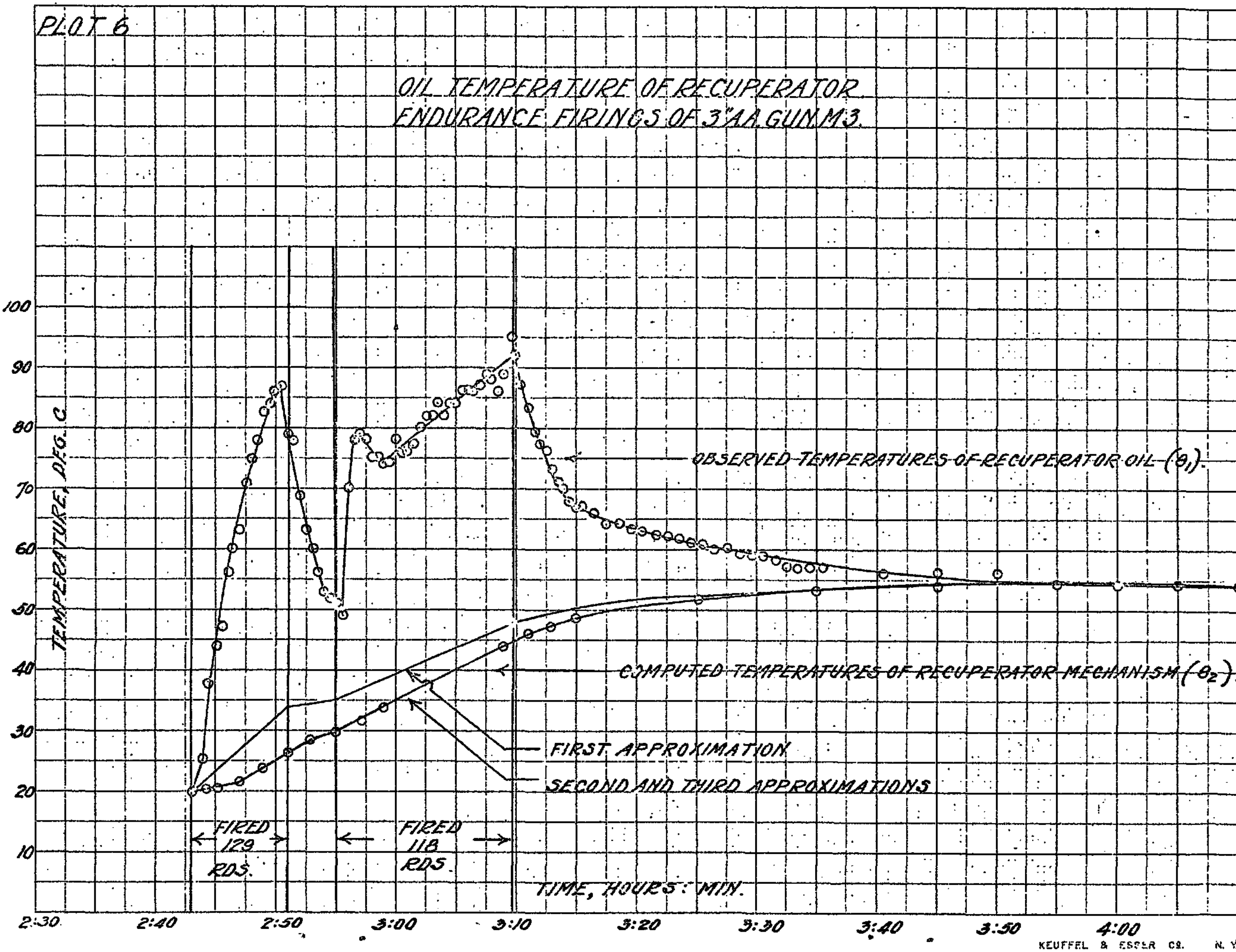


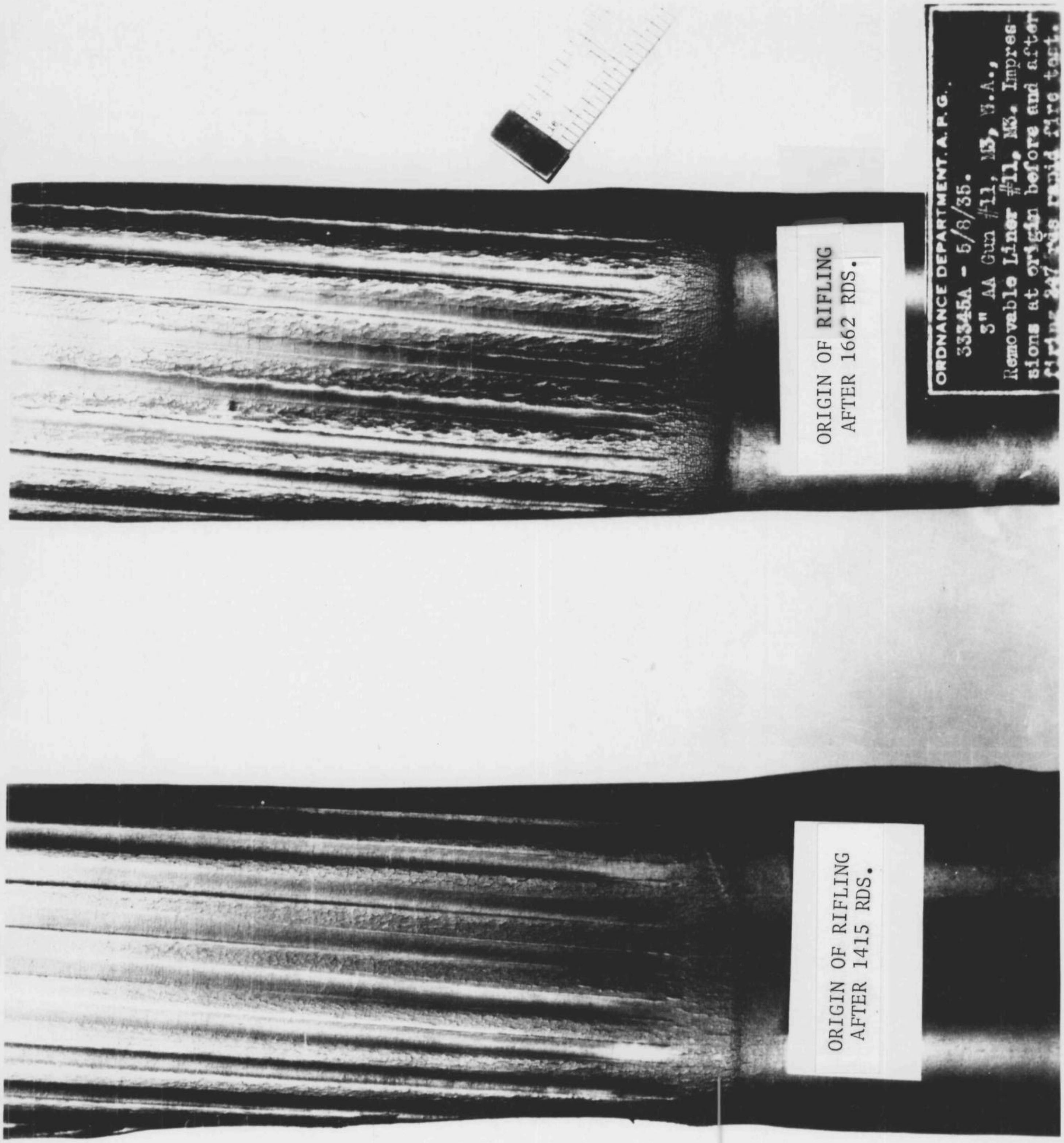

PLOT 3
EROSION OF LANDS AND GROOVES
OF
3" A.A. GUN. M3. NO. 11
DIAMETER OF GROOVES, INCHES.
3.120
3.100
3.080
GROOVES
DIAMETER OF LANDS, INCHES.
3.100
3.080
3.060
3.040
3.020
3.000
2.980
LANDS
— BEFORE FIRING
△ AFTER 1415 ROUNDS
□ AFTER 1662 ROUNDS
(ROUNDS 1416 - 1662 WERE 247 ROUNDS OF RAPID FIRE)
DISTANCE FROM BREECH, INCHES.
0
50
100
150
KEUFFEL & ESSER CO.

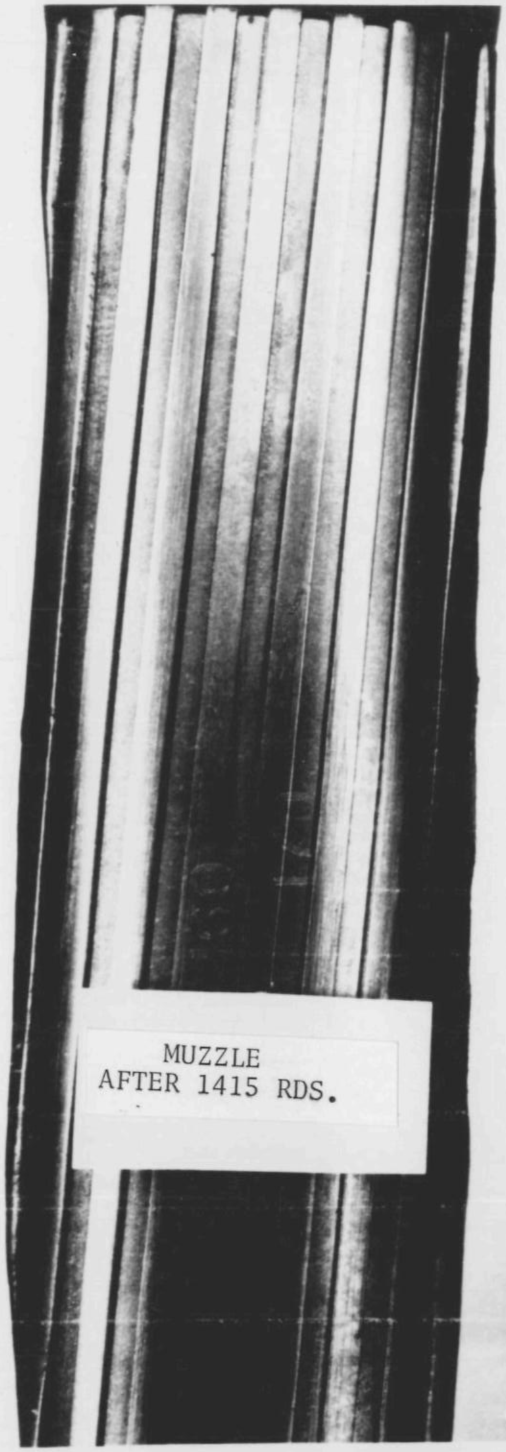


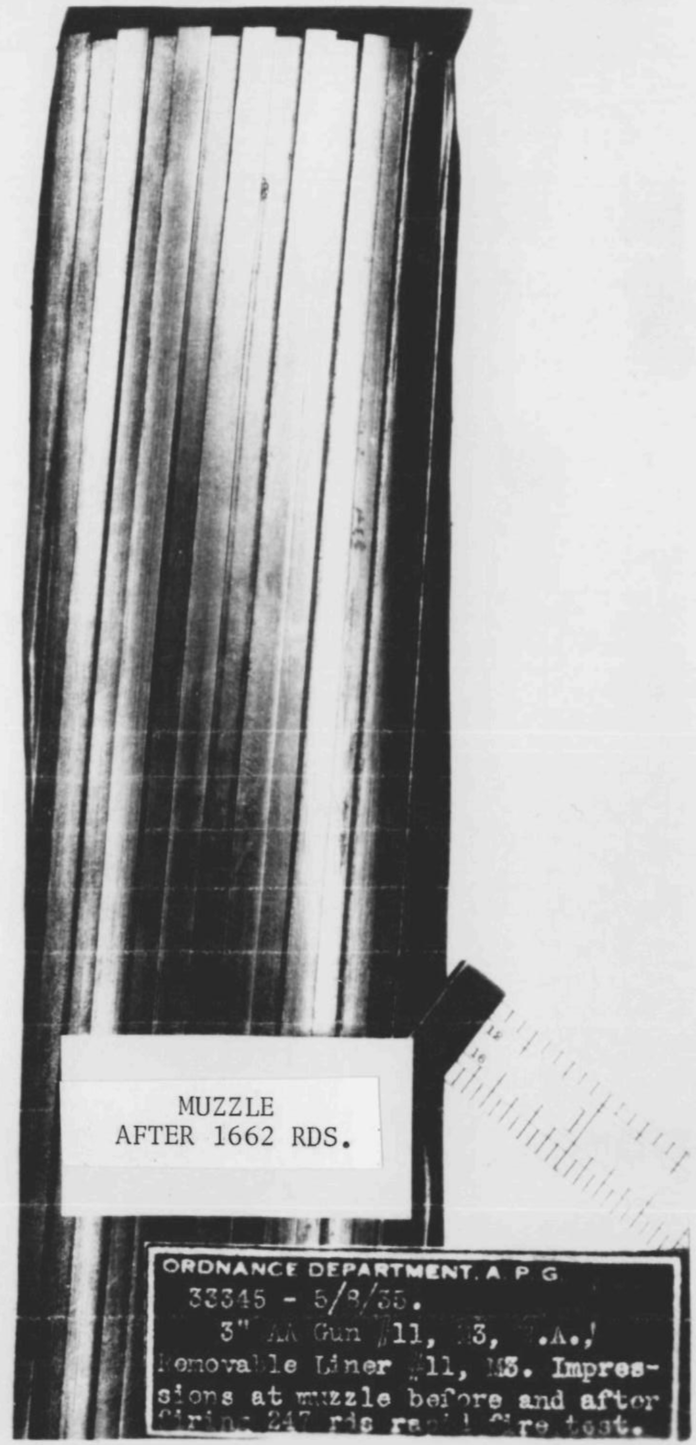
KEUFFEL & ESSER CO.


PLOT 5
CALCULATED TEMPERATURES OF THE
3" A.A. GUN, M3, AT VARIOUS RATES OF FIRE
TEMPERATURE, DEG. C (EXCESS ABOVE ATMOSPHERIC)
TIME, MINUTES
20 RDS/MIN.
15 RDS/MIN.
10 RDS/MIN.
5 RDS/MIN.
O 1.08 FEET FROM MUZZLE
Δ 5.21 FEET FROM MUZZLE
0
100
200
300
400
500
600
25
50
75
100
KEUFFEL & ESSER CO.


PLOT 6
OIL TEMPERATURE OF RECUPERATOR
ENDURANCE FIRINGS OF 3" AA GUN M3.
OBSERVED TEMPERATURES OF RECUPERATOR OIL (θ_1).
COMPUTED TEMPERATURES OF RECUPERATOR MECHANISM (θ_2)
FIRST APPROXIMATION
SECOND AND THIRD APPROXIMATIONS
FIRED 129 RDS.
FIRED 118 RDS.
TEMPERATURE, DEG. C
TIME, HOURS : MIN.
10
20
30
40
50
60
70
80
90
100
2:30
2:40
2:50
3:00
3:10
3:20
3:30
3:40
3:50
4:00
KEUFFEL & ESSER CO. N. Y.


ORDNANCE DEPARTMENT. A. P. G.
33345A - 5/8/35.
3" AA Gun #11, M3, W.A.,
Removable Liner #11, M3. Impressions at origin before and after
firing 247 rds rapid fire test.
ORIGIN OF RIFLING AFTER 1662 RDS.
ORIGIN OF RIFLING AFTER 1415 RDS.


MUZZLE
AFTER 1415 RDS.


MUZZLE
AFTER 1662 RDS.
ORDNANCE DEPARTMENT. A. P. G.
33345 - 5/8/35.
3" AA Gun #11, M3,
Removable Liner #11, M3. Impressions at muzzle before and after
rds rapid fire test.